MIMO techniques for improving diversity and spatial multiplexing in vehicular networks

Nicholas Prodromou

June 26, 2015

Abstract

In this work, we evaluate the performance of MIMO systems and techniques compared to SISO system in VANETs. The goal of this work is to investigate whether MIMO systems can be configured to achieve higher throughput or/and better reliability. Of particular interest in this work is the minimization of the effect of RF jamming in the effective range of the transmitter and receiver communication pair.

To my family and friends

Acknowledgements

Upon completion of my thesis, I would like to thank my supervisor Dr. Argiriou Antonios and my co-supervisor Dr. Korakis Athanasios, for their trust and excellent cooperation we have had during this project and my studies. I would also like to thank Ph.D. candidate Kosmanos Dimitris for his assistance and guidance to this work.

Finally, I would like to thank my family and friends for their support all these years.

Contents

1 Introduction and System Model **7**

1.1 Introduction 7

1.2 Beyond related works 8

1.3 System model 8

2 Proposed system **10**

2.1 MRC Receive Diversity 10

2.2 Alamouti Space-Time Block Code(STBC) technique Transmit Diversity 11

2.2.1 Classic Alamouti algorithm 11

2.2.2 Alamouti implementation, in a more than 2 transmit antennas system 12

2.3 Spatial Multiplex 13

2.3.1 Classic Spatial Multiplex technique 13

2.3.2 Modified version of Spatial Multiplex 14

2.4 Optimal configuration for a MIMO system 14

3 Performance evaluation **15**

3.1 Overview of experiments 15

3.2 GEMV and VEINS comparison 17

3.3 First Experiment (Experiment1) 18

3.4 Second Experiment (Experiment2) 23

4 Conclusions **28**

5 References **30**

List of Figures

3.1 GEMV vs VEINS snr estimation. 17
3.2 GEMV vs VEINS snr estimation. 18
3.3 Case 1 of Experiment 1 20
3.4 Case 2 of Experiment 1 21
3.5 Case 3 of Experiment 1 22
3.6 Case 1 of Experiment 2 25
3.7 Case 2 of Experiment 2 27

List of Tables

3.1 802.11p Data Rates and corresponding modulation and coding schemes . . . 16
3.2 Simulation Parameters . . . 16
3.3 802.11p header and OFDM parameters . . . 17

Chapter 1

Introduction and System Model

1.1 Introduction

Vehicular Ad-hoc Networks (VANETs) are growing every day. The main reason for this is the advanced safety provided to drivers by earning some crucial seconds for drivers reaction or even overlapping human fault, in other cases. But VANETs may also offer luxury to passengers, by providing internet access to them.

802.11a protocol was modified to meet vehicular networks requirements and conditions, renders it reliable to use and research purposes. This was standardized as 802.11p protocol and its used in VANETs.

Nowadays the cost of RF hardware is not prohibitive to install more complex systems. This way we could manage the increase of spatial diversity. Diversity is the main key to achieve improved performance.

For these reasons our experiments focus on evaluating how Multiple Input Multiple Output (MIMO) systems can improve robustness in RF jamming threats and simultaneously achieve higher throughput rates. We try to overcome and minimize threats effect by making use of MIMO systems across with dedicated transmission algorithms.

Combining MIMO system with the existing Orthogonal Frequency-Division Multiplexing (OFDM) technology we manage to increase diversity in all possible directions and that results in remarkable performance improvement. This is the solution for problems such as multipath fading affecting considerably reliability of V2V communication.

1.2 Beyond related works

A lot of work has been conducted in the research area of MIMO in VANETs and Jamming in a number of vehicles that communicate with each other.

The first group of works, mainly focuses on explaining the benefits of using MIMO in VANETs [1], examine propagation models [2] [4] and physical layers suitable for MIMO systems [3].

Regarding Jamming in VANETs, the main purpose was to analyze threats and focus on the effects of RF jamming [6], [7]. Based on these works, we chose the constant jammer for our experiments which has the greater impact. Some experiments have been made to compare different RF jamming threat types [5]. Another one is describing some video applications further than entertainment but for safety purposes [8]. A part of our experiments focuses on enhanced video streaming, because of its importance.

All these works gave us useful information but none of them has covered the case of using MIMO system and techniques to overcome these threats. Thats the gap this work tries to fill out. Based on the knowledge of related works, we properly set up our system model in order to study the performance of MIMO systems and techniques compared to SISO systems in VANETs. Specifically , our scheme (vSP4) with the better diversity gain offers a a fine Packet Delivery Ratio (PDR) with SINR 10dB less than that it used in [5] to succeed the 100% PDR value.

1.3 System model

The model used to run experiments is based on VEINS 3.0 and SUMO 0.21.0 projects to simulate vehicular network and create custom scenarios. Also, instead of using simplified VEINS measures at the PHY layer we selected a Veins network simulator - GEMV2 (a Geometry-based Efficient propagation Model for V2V) integration. This simulator uses a Ray-tracing method, require a detailed description of the propagation environment, to produce the actual physical propagation process for a given environment, to accurately calculate the channel statistics. The reason for this was to take advantage of detailed environment parameters for more accurate and as realistic estimations as possible. In later section we will see a comparison of GEMV estimations to VEINS estimations. In order to succeed that, GEMV was configured and modified to suite to our area environment and conditions.

Since the point of inspire and comparison was the publication **"Experimental Characterization and Modeling of RF Jamming Attacks on VANETs"**, same road in Aachen was focused to run our experiments with most of parameters kept the same. Some parameters changed for better simulation and smoother visual results. In our scenario we always sent 10 packets per second. Next, we calculate the average SNR for 1s and run our experiments.

Experiments used 802.11p protocol parameters and the rest parameters were set up such as transmission power, were defined as in [1]. Refer to Table 3.1, 3.2, 3.3 for details of parameter values. Also, Rayleigh fading channels with Additive White Gaussian Noise (AWGN), stable for time of 10 symbols was assumed. Experiment simulation to calculate Bit Error Rate (BER) was based on $5 * 10^3$ QPSK/16-QAM symbols. As noticed by experimentation, higher the number of samples, much more is the amount of time that needed to run the experiments, without significantly improving statistical errors. Modulation schemes and data rates used were 3Mbps for packet header and 6Mbps or 18Mbps for packet payload which are currently supported by VEINS project.

Chapter 2

Proposed system

As mentioned earlier, MIMO systems may achieve higher throughput or/and reliability. Without any dedicated method of transmission, MIMO still performs better than Single Input Single Output (SISO) system. But in order to reveal the maximum capabilities for the best performance to serve our each case needs, dedicated transmission algorithms should be applied.

2.1 MRC Receive Diversity

On receivers side, we combine each antennas received signal with the technique Maximum Ratio Combining (MRC), which combines signals by a weight in order to achieve higher mean SNR. The following mathematical equations describe this technique, based on pre-mentioned parameters.

$$\vec{y} = \vec{h}x + \vec{z} \tag{2.1}$$

$$\tilde{y} = \vec{s^H}\vec{y} = \vec{s^H}\vec{h}x + \vec{s^H}\vec{z}(2.2)$$

That leads to achieve instantaneous SNR:

$$\gamma = \frac{E_b|\vec{s^H}\vec{h}|^2}{E_b[|\vec{s^H}\vec{z}|^2]} \tag{2.3}$$

According to Cauchy-Schwarz inequality $|\vec{s^H}\vec{h}|$ has a maximum when $\vec{s}$ is linearly proportional to $\vec{h}$. So by setting it equal $\vec{s} = \vec{h}$ we have:

$$\gamma = \frac{E_b|\vec{h^H}\vec{h}|^2}{\sigma^2||\vec{h}||^2} = \frac{E_b|\vec{h^H}\vec{h}|^2}{\sigma^2\vec{h^H}\vec{h}} = \frac{E_b\vec{h^H}\vec{h}}{\sigma^2\vec{h^H}\vec{h}} = \sum_0^{N-1}\frac{E_b|h_n|^2}{\sigma^2} = \sum_0^{N-1}\gamma_n \tag{2.4}$$

Thats the sum of the SNR at each element.

2.2 Alamouti Space-Time Block Code(STBC) technique Transmit Diversity

2.2.1 Classic Alamouti algorithm

On Transmitters side we use more complex and advanced algorithms. There are a lot of transmission methods that are being studied and researched, but one of the most popular and efficient method is the Alamouti STBC technique.

Alamouti requires at least 2 transmit antennas. It does not improve throughput in terms of absolute numbers, but achieves significantly lower BER. As a result, we manage to transmit data in channels where was impossible or at least very difficult with the ordinary SISO system. In that way we can say that this method also improves throughput in bad conditions channels. To make this happen, we transmit 2 symbols (u1, u2) orthogonally. Right after that, we retransmit them from the other antenna, orthogonally again, in the next timeslot as shown in the Table below:

TxId/TimeSlot	T1	T2
Tx1	u1	u2
Tx2	-u2*	u1*

Because of orthogonal transmission, two symbols do not interfere each other. Finally, we succeeded to send each symbol twice without any impact to maximum throughput. Following equations, issue on a 2x1 MISO system will make it clear why this technique is particularly popular. Actual received signals:

$$\begin{bmatrix} y_1 & y_2 \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \begin{bmatrix} u_1 & -u_2^* \\ u_2 & u_1^* \end{bmatrix} + \begin{bmatrix} w_1 & w_2 \end{bmatrix} \tag{2.5}$$

$$\tilde{y} = \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -u_1^* \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} = H\vec{u} + \vec{w} = \vec{r}$$

(2.6)

Because the columns of this matrix are orthogonal, equation can be rewritten as:

$$\vec{y} = \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2^* \end{bmatrix} u_1 + \begin{bmatrix} h_2 \\ -h_1^* \end{bmatrix} u_2 + noise \tag{2.7}$$

Finally, decoding with MRC we get:

$$\begin{aligned} \tilde{r} = H^H (h^{\vec{H}}\vec{h})^{-1}\ \vec{\tilde{y}} &= \frac{1}{||\vec{h}||^2} \begin{bmatrix} h_1^* & h_2 \\ h_2^* & -u_1 \end{bmatrix} \vec{\tilde{y}} \\ &= \frac{1}{||\vec{h}||^2} \begin{bmatrix} |h_1|^2 + |h_2|^2 & 0 \\ 0 & |h_1|^2 + |h_2|^2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} \tilde{}w_1 \\ \tilde{u_2} \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} \tilde{w_1} \\ \tilde{u_2} \end{bmatrix} \end{aligned} \tag{2.8}$$

Because of MRC technique on receive antennas, its obvious that as the number of receive antennas grows, better result is expected.

2.2.2 Alamouti implementation, in a more than 2 transmit antennas system

On the other hand, on transmitters side, there is more variety on how to configure these antennas for optimized performance, based in each case demands. Alamouti technique is not an exception in more than 2 transmission antennas system. A lot of variations of alamouti appliance in higher order MIMO systems can be found.

In this work a novel technique that increase the diversity gain is implemented when MIMO system has more than 2 transmission antennas. Each odd numbered antenna transmits what Tx1 transmits, and even numbered antenna transmits what Tx2 transmits. In that way the diversity gain is even higher since each symbol is transmitted more times and from different channels. In that case, equation (2.8) is still valid with the substitution of

$$h_1 = \sum_{1}^{N} h_i, i = 1, 3, 5, \dots N \tag{2.9}$$

and

$$h_2 = \sum_{2}^{N} h_i, i = 2, 4, 6, \dots N \tag{2.10}$$

It is not so obvious obvious why this change is so important and helpful, instead of useless extra and more complex calculations. To realize that, we need to keep in mind, that the mean value of Rayleigh distribution channels equals 1. So with this change, as the Tx antennas are increased, the probability of inverse matrix existence increases too. Consequently makes the calculation of the inverse or pseudo-inverse matrix, as shown in the final step of (2.8), lot of easier and accurate. That method is more suitable for transmissions under bad conditions such as NLOS channel or under jamming environments.

2.3 Spatial Multiplex

2.3.1 Classic Spatial Multiplex technique

But what happens when it is more preferable the increased throughput instead of reliability, such as video delivery applications in VANETs that are be targeted either to safety either to infotainment. The method which offers that is Spatial Multiplex. Its quite simple in fact. Each transmission antenna transmits a different symbol. So in case of 2, 4 or N antennas, we manage to double, quadruple or N-times throughput respectively. Simplicity of this technique offers a big improvement, but needs higher SNR/SNIR values. In other cases high rate of transmission errors will occur, making communication impossible. This happens because in a way, this method interferes itself by transmitting simultaneously different symbols. Following equations will help to see this technique in theoretical level. MIMO channel model:

$$\vec{y} = H\vec{x} + z \tag{2.11}$$

We apply Least Squares Equalization to H by multiplying with the pseudo-inverse matrix $H^{\dagger}$:

$$H^\dagger = (H^H H)^{-1} H^H \quad (2.12)$$

So we get to:

$$\vec{r} = (H^H H)^{-1} H^H \vec{y} = x + (H^H H)^{-1} H^H \vec{z} \quad (2.13)$$

which is known as zero-forcing method. Also, when H is square and invertible then $H^\dagger = H^{-1}$

2.3.2 Modified version of Spatial Multiplex

In this work this technique was implemented with a variation. User may choose a slower but more reliable method to transmit, by choosing how many different symbols wants to transmit in each timeslot. The rest of antennas will repeat these symbols achieving higher probability of correct transmission to the receiver. For example, in a 4x4 MIMO system normally wed transmit 4 symbols per timeslot. We may choose though to transmit 2 symbols per timeslot in order to double instead of quadruple our maximum throughput but gaining a more robust communication . In this case we have higher transmit diversity. Same principles as described in 2.2.2 subsection issue again, without alamoutis coding characteristics.

2.4 Optimal configuration for a MIMO system

As well see in later section target of maximizing throughput is not always the best tactic. In cases of throughput demanding applications, e.g. video streaming, the best choice is to use MIMO system to upgrade throughput to the demanded speed and use the rest of antennas either inactive to decrease interference, either to improve diversity as in our case. Fully speed up of throughput is needless and is much more vulnerable to environment changes, that is the most common characteristic of vehicular environments.

Chapter 3

Performance evaluation

3.1 Overview of experiments

Since we evaluate and ensured that our configurations and scenarios were setup correctly, we executed two main experiments.

In the first one, the transmitter (Tx) is static and receiver (Rx) is moving towards a jammer node (Jn) which is also static. The purpose of this experiment is to evaluate how the communication range is affected by the presence of an RF jamming threat under different communication rate requirements.

In the second scenario, Tx and Rx are moving keeping constant distance between them, 20m 50m and 100m, towards Jn which is not moving. The purpose of this experiment is to see how RF jamming threat may affect or even silence communication when the communication pair passes through its effective range and how pre-mentioned methods manage to suppress its effect. A sub-category of this experiment was run to compare the performance of 2x2 MIMO to 4x4 MIMO, transmitting with the variations of Spatial Multiplex technique, in the distance of 100m between communication pair.

Alamouti technique was out of the comparison since it performs more and more robust as number of antennas of MIMO system is increased but keeps throughput stable. In cases of emergencies or very high interfering channels is the absolute winner. Target is to examine if it's achievable to support video streaming applications under hostile channel conditions. Details about experiment parameters can be found on the following Tables 3.1, 3.2, 3.3.

802.11p Data Rates	
3 Mbps	BPSK 1/2
4.5Mbps	BPSK 3/4
6 Mbps	QPSK 1/2
9 Mbps	QPSK 3/4
12 Mbps	16-QAM 1/2
18 Mbps	16-QAM 3/4
24 Mbps	64-QAM 2/3
27 Mbps	64-QAM 3/4

Table 3.1: 802.11p Data Rates and corresponding modulation and coding schemes

PARAMETER	VALUE
Transmitter Power	17.48 dBm
Jammer Power	16.75 dBm
Packet Generation rate [packets/s]	10
Simulation Symbols Number	5000
Data rates in experiments	6Mbps or 18Mbps
Packet Payload	100B or 400B

Table 3.2: Simulation Parameters

802.11p header and OFDM in 802.11p parameters at 5.9GHz (10Mhz)	
Subcarrier Number	48
Pilot Subcarrier Number	4
Subcarrier frequency spacing	156.25 KHz
Guard Interval	1.6 s
Symbol Interval + Guard Interval	8 s
Preamble Time	32 s
Signal field Time	8 s
Service Field	2B
MAC Address	24B
WAVE Short Message Protocols (WSMP)	8B
FCS field	4B
Tail	6bits

Table 3.3: 802.11p header and OFDM parameters

3.2 GEMV and VEINS comparison

Before running our experiments, a comparison of GEMV to VEINS SNR estimations was made to see the differences and make sure that a better realization of channel propagation is showed using GEMV.

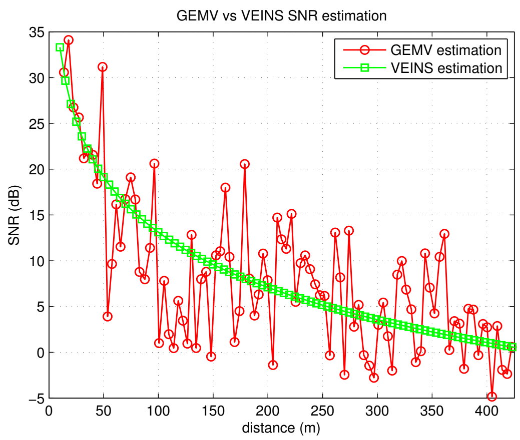


Figure 3.1: GEMV vs VEINS snr estimation.

As shown in Figure 3.1, GEMV uses more detailed algorithm to calculate SNR value, taking care of other vehicles and obstacles. VEINS uses a simple log-distance model without considering environment conditions. To check if our scenario is properly configured and working correctly, Figure 3.2 was created to check if SNIR changes under RF jamming effect.

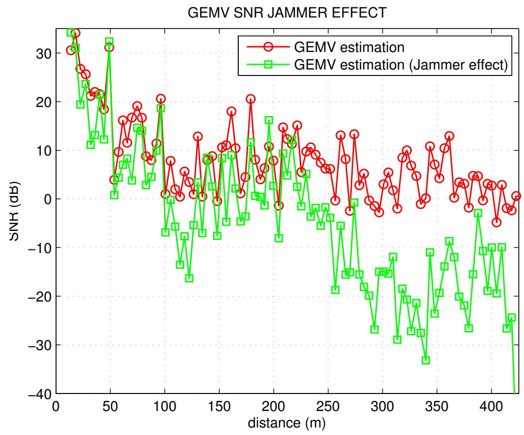


Figure 3.2: GEMV vs VEINS snr estimation.

While Rx moving further from Tx and getting closer to Jn, we expect to see SNIR getting worse and thats what Figure 3.2 exactly shows. So, everything is ready to execute experiments.

3.3 First Experiment (Experiment1)

First case of this experiment is to compare performance of 2x2 MIMO system to SISO system, under same conditions and configurations as in [6] constant jammer case and described in Table 3.2, Table 3.3, for payload of 100B @ 6Mbps.

As a result, viewing Figure 3.3(a) we may see the SNR gain of Alamouti technique compared to the others making it more reliable and robust. We also notice that Spatial Multiplex doubles throughput but with a cost of SNR loss. Figures 3.3(b),3.3(c) and Figures 3.3(d), 3.3(e) reveal the impact of RF jamming threat in PDR and throughput respectively and how MIMO system techniques manage to overcome or suppress it.

As larger is the packet we transmit such more possible is to receive it with errors. But we benefit from the less overhead. In conclusion, there is always the tradeoff of choosing the packet length which will maximize performance.

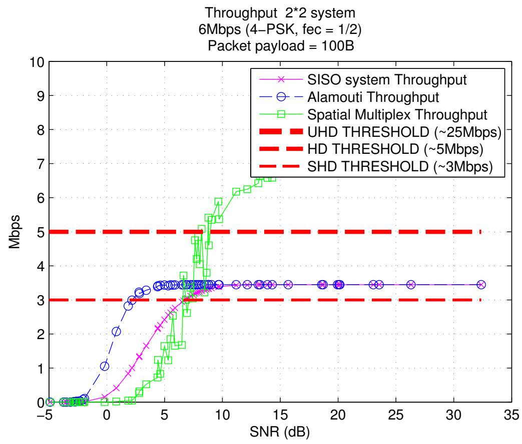
Thats our second case of this experiment. Having 400B payload @ 6Mbps executed on the same input data as case1, in order to examine the results in a higher throughput demanding communications.

Figure 3.4(a) compared to Figure 3.3(a), shows that maximum throughput was increased, as expected. The important here is the impact in low SNR channels. Figures 3.4(b), 3.4(c) and Figures 3.4(d), 3.4(e) will help to compare results of PDR and throughput respectively as earlier but are also useful to compare with the previous case results to make clear the impact of payload to these metrics. A note here is that High Definition (HD) video streaming requires about 5Mbps. By examining these first results we noticed that because of packet header length and OFDM overhead, in case of 100B of payload is theoretically possible to be supported only by Spatial Multiplex. But this requires high SNR channels and its quite unstable so this choice isnt really suitable. In case of 400B payload, we can see clearly alamoutis remarkable performance. Very stable and may support HD rates since the low of about 5dB of SNR instead of about 10dB SISO system needs. That dB gain is enough to extend significantly the communication range.

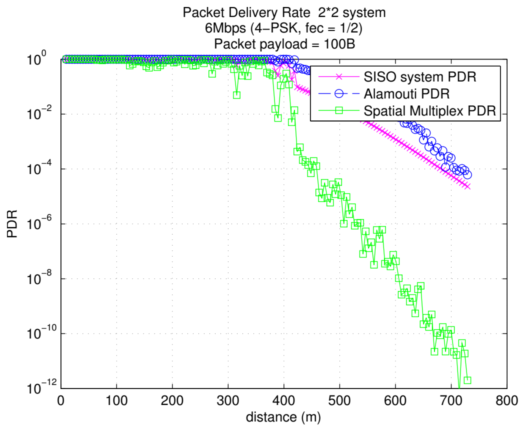
As an extension of the previous, the third case of experiment is executed under of 400B payload @ 18Mbps. Before execution, simulation was run again for that scenario, to get the proper input data for the new modulation scheme.

By examining Figure 3.5(a), there are two important observations. Firstly all techniques almost triple their maximum throughput. In alamouti and SISO case does not really makes any difference for our application. But in Spatial Multiplex case, reveals techniques advantages. We managed to reach about 26Mbps which is higher than Ultra HD (UHD) threshold, at about 25Mbps rate, with a modulation scheme which was impossible without MIMO system to be supported.

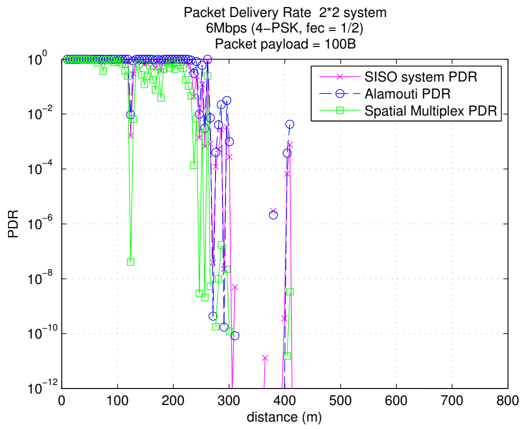
The second one is that we see the SISO system to be affected by the modulation and coding scheme a lot more than the other two MIMO system techniques. In Figures 3.5(b), 3.5(c) and Figures 3.5(d), 3.5(e) its obvious even without interference that SISO system in real conditions behaves badly and communication range is seriously reduced compared to the previous case. MIMO techniques seem to have been barely affected by the change of the modulation and coding scheme.



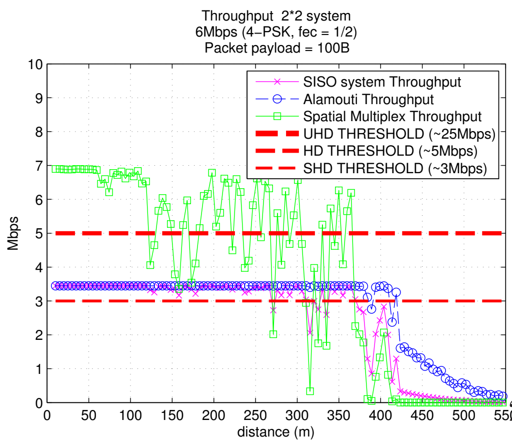
(a) Case 1 of Experiment 1, Throughput to SNR (100B@6Mbps)



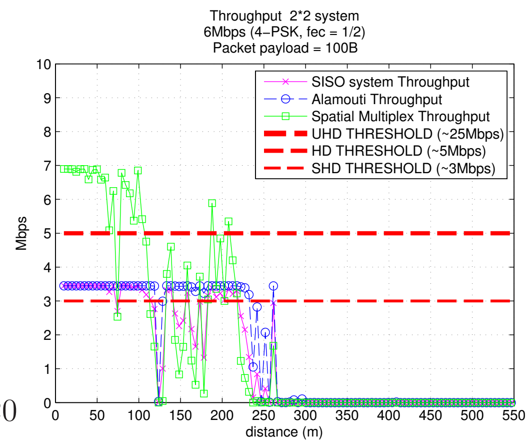
(b) Case 1 of Experiment 1, PDR to Tx-Rx pair distance, without interference (100B@6Mbps)



(c) Case 1 of Experiment 1, PDR to Tx-Rx pair distance, with interference (100B@6Mbps)

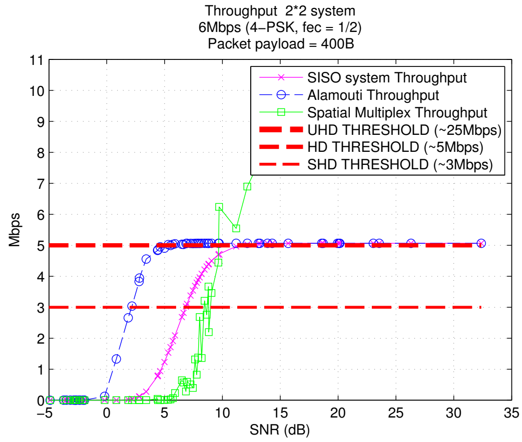


(d) Case 1 of Experiment 1, Throughput to Tx-Rx pair distance, without interference (100B@6Mbps)

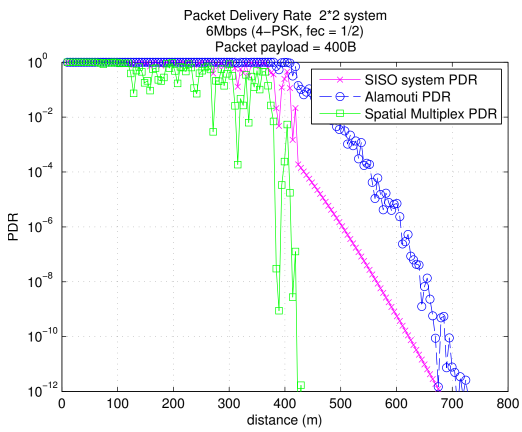


(e) Case 1 of Experiment 1, Throughput to Tx-Rx pair distance, with interference (100B@6Mbps)

Figure 3.3: Case 1 of Experiment 1

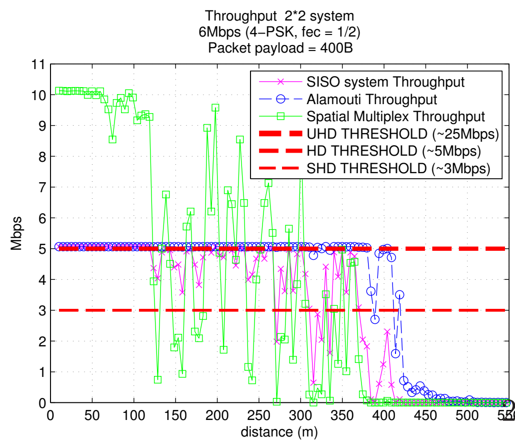


(a) Case 2 of Experiment 1, Throughput to SNR (400B@6Mbps).

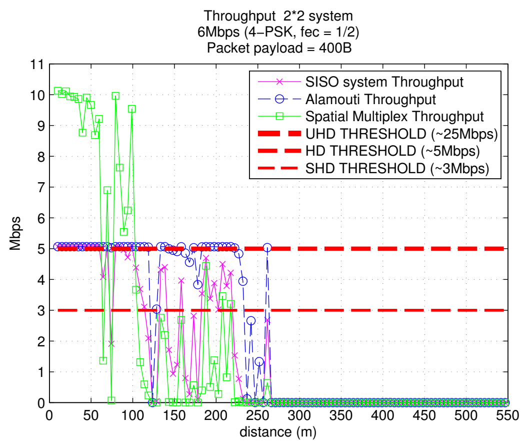


(b) Case 2 of Experiment 1, PDR to Tx-Rx pair distance, without interference (400B@6Mbps)

(c) Case 2 of Experiment 1, PDR to Tx-Rx pair distance, with interference (400B@6Mbps)

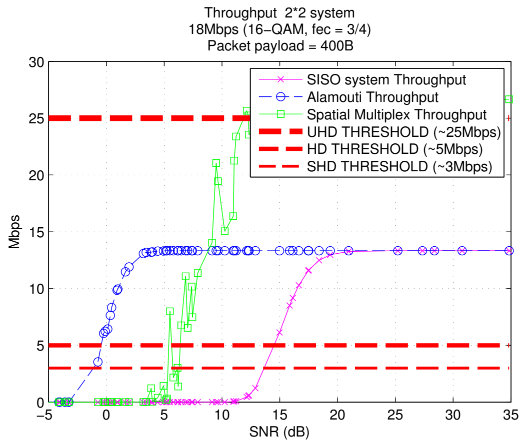


(d) Case 2 of Experiment 1, Throughput to Tx-Rx pair distance, without interference (400B@6Mbps)

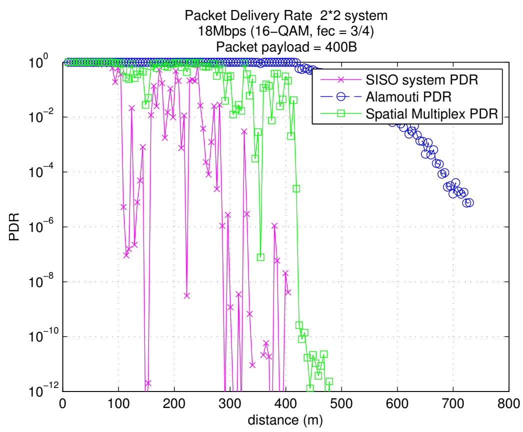


(e) Case 2 of Experiment 1, Throughput to Tx-Rx pair distance, with interference (400B@6Mbps)

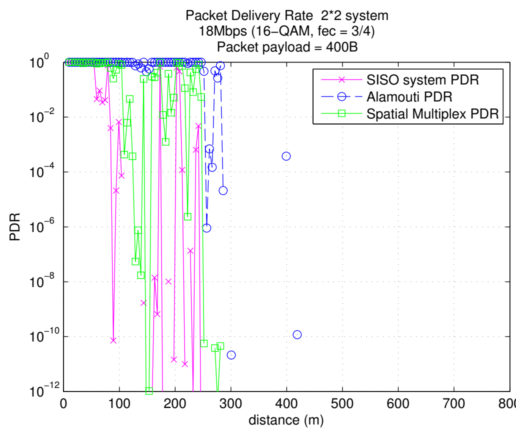
Figure 3.4: Case 2 of Experiment 1



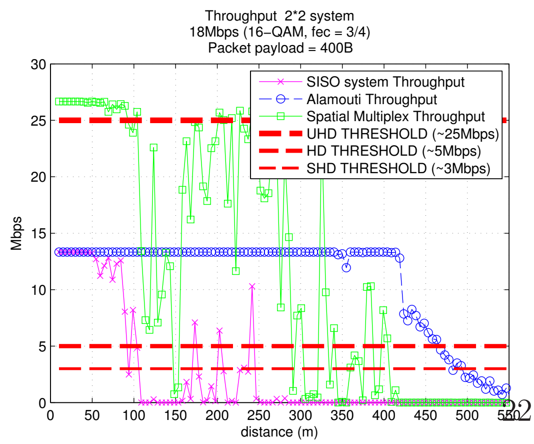
(a) case 3 of Experiment 1, Throughput to SNR (400B@18Mbps).



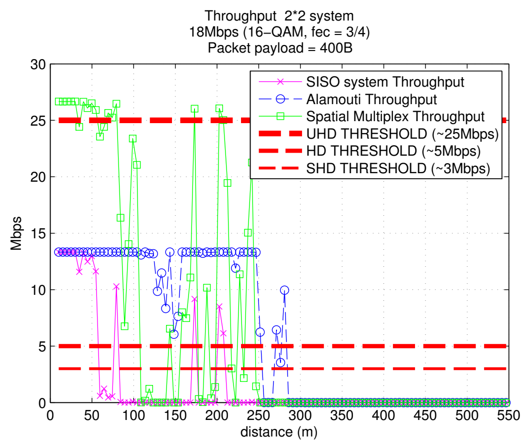
(b) case 3 of Experiment 1, PDR to Tx-Rx pair distance, without interference (400B@18Mbps)



(c) case 3 of Experiment 1, PDR to Tx-Rx pair distance, with interference (400B@18Mbps)



(d) case 3 of Experiment 1, Throughput to Tx-Rx pair distance, without interference (400B@18Mbps)



(e) case 3 of Experiment 1, Throughput to Tx-Rx pair distance, with interference (400B@18Mbps)

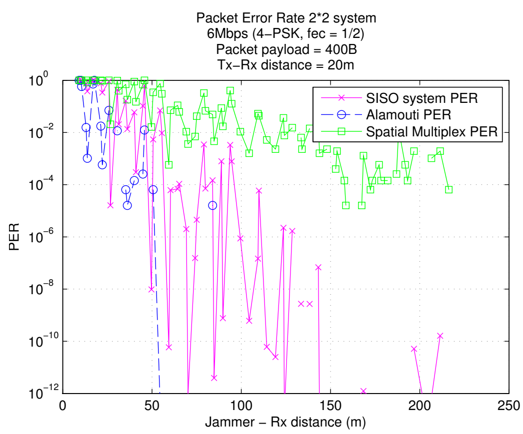
Figure 3.5: Case 3 of Experiment 1

3.4 Second Experiment (Experiment2)

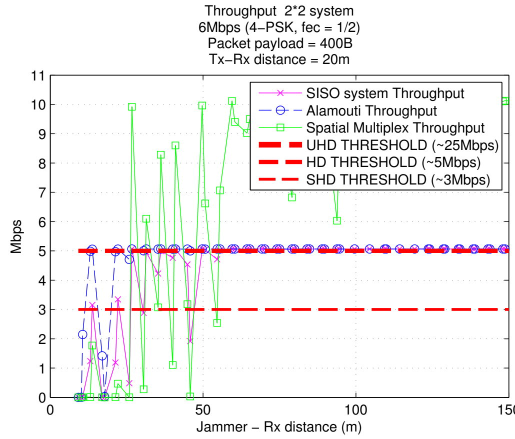
In this experiment 400B payload @ 6Mbps was chosen, because as we saw earlier, is harder to transmit this packet correctly than 100B payload. This will allow us see jammer effect and MIMO improvement more clearly. Comparison at short, mid and long distances between communication pair of Tx - Rx was made and resulted Figures 3.6(a) - 3.6(i). In this experiment Packet Error Rate (PER) metric was more suitable than PDR to observe the results. Also, Figures of Throughput to Time were introduced to see the silence time of communication caused by Jammer.

As expected, while Tx - Rx distance is increased, RF jamming impact is dramatically increased. Also, once again we can see the benefits and the improved performance of MIMO system. In case of short distance, where there is the least impact in communication, alamouti technique manages to suppress RF jamming threat silence range at about 10m or in just a few seconds.

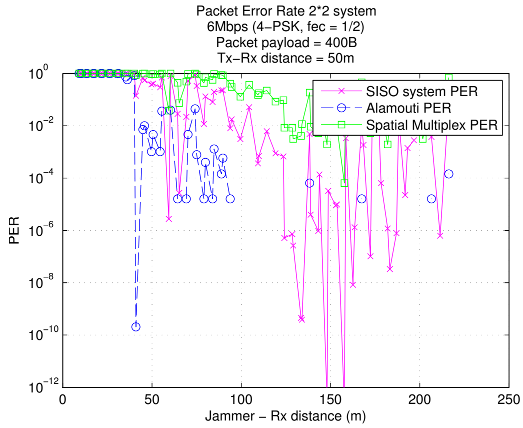
This experiment also reveals the limits of 2x2 MIMO systems. Especially in 100m distance, even alamouti technique fails to suppress that effect. Silence distance extends a lot. In time domain, the impact is the communication to be corrupted for about 20s. In environments like this, usually achieving high throughput isnt the first priority. Imagine an emergency to occur and vehicle communication be out of availability. Unable to contact or warn other nodes for such a long distance or time if it is an emergency on the move causing traffic jam and traffic accidents.



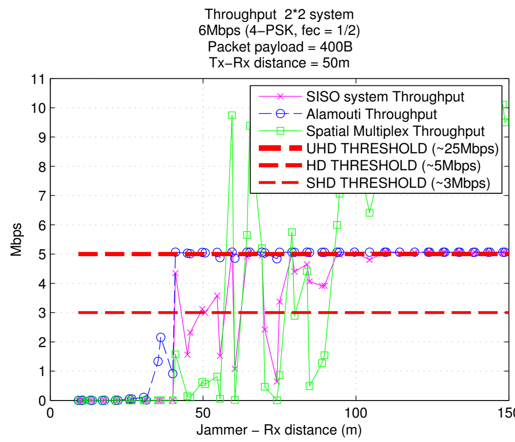
(a) Case 1 of Experiment 2. PER to Rx-Jn pair distance. Tx-Rx pair distance = 20m



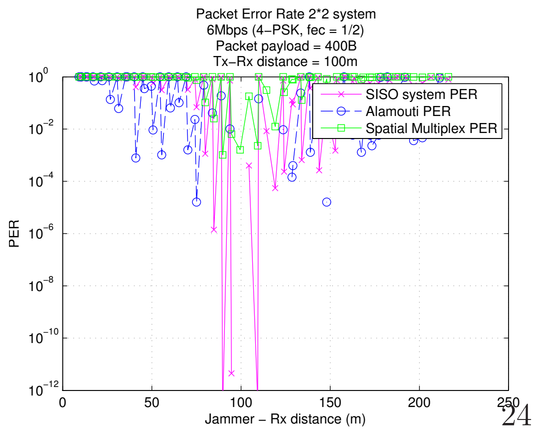
(b) Case 1 of Experiment 2. Throughput to Rx-Jn pair distance. Tx-Rx pair distance = 20m



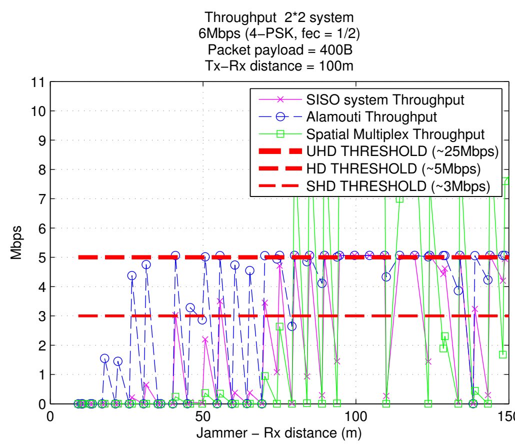
(c) Case 1 of Experiment 2. PER to Rx-Jn pair distance. Tx-Rx pair distance = 50m



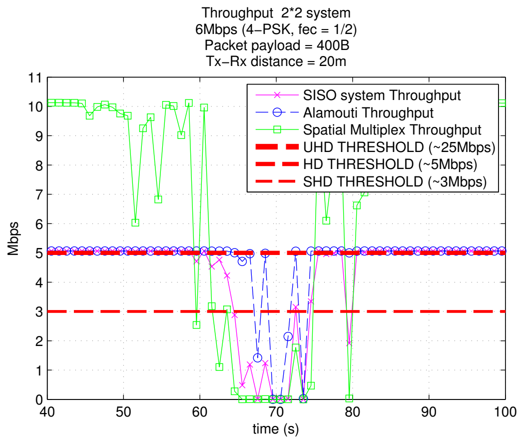
(d) Case 1 of Experiment 2. Throughput to Rx-Jn pair distance. Tx-Rx pair distance = 50m



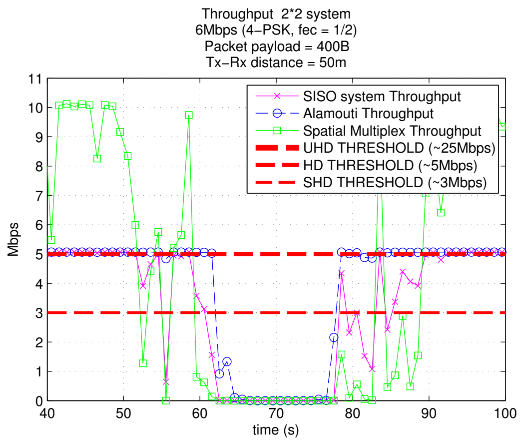
(e) Case 1 of Experiment 2. PER to Rx-Jn pair distance. Tx-Rx pair distance = 100m



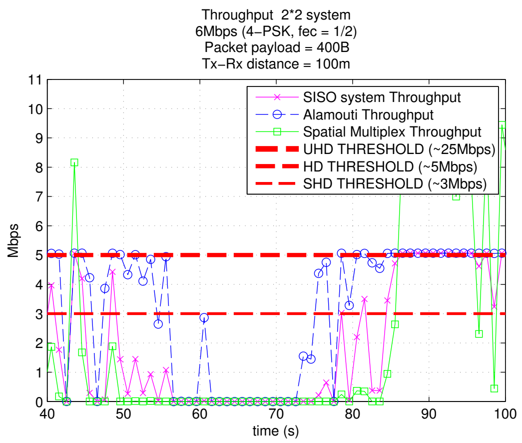
(f) Case 1 of Experiment 2. Throughput to Rx-Jn pair distance. Tx-Rx pair distance = 100m



(g) Case 1 of Experiment 2. Throughput to Time. Tx-Rx pair distance = 20m



(h) Case 1 of Experiment 2. Throughput to Time. Tx-Rx pair distance = 50m



(i) Case 1 of Experiment 2. Throughput to Time. Tx-Rx pair distance = 100m

Figure 3.6: Case 1 of Experiment 2

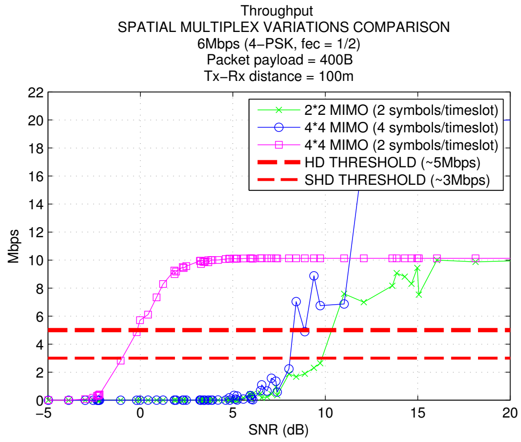
That leads to our final case of experiment. Trying to overcome RF jamming threat by introducing in experiment 4x4 MIMO system. Alamoutis performance, as described in 2.2.2 subsection, was beyond of what we expected. Excellent performance regarding robustness.

So this case focused on trying to improve both robustness and throughput by comparing Spatial Multiplex variation, as described in 2.3.2 subsection. Note that PDR metric is used again instead of PER for better visual observations. In figures 3.7(a) - 3.7(e), comparison is made between:

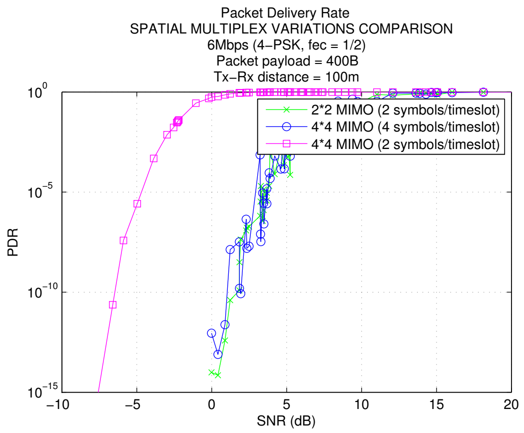
- 2x2 MIMO classic version of Spatial Multiplex (cSP2), transmitting two symbols simultaneously.
- 4x4 MIMO classic version of Spatial Multiplex (cSP4), transmitting four symbols simultaneously.
- 4x4 MIMO variation of Spatial Multiplex (vSP4), transmitting 2 symbols simultaneously. Each symbol is transmitted by two antennas the same time.

Figure 3.7(a) brings out the first results. SNR gain of vSP4 is huge. Figure 3.7(b) leads to have a better opinion of cSP2 compared cSP4. This comparison has kind of unexpectedly positive results. While cSP4 provides double throughput compared to cSP2, it does not need higher SNR values to perform well. It even performs slightly better than cSP2 regarding SNR requirements. That mainly happens because in this case we also doubled receive diversity which balances the higher SNR need. Figure 3.7(c) shows how these SNR performances are translated into VANET environments.

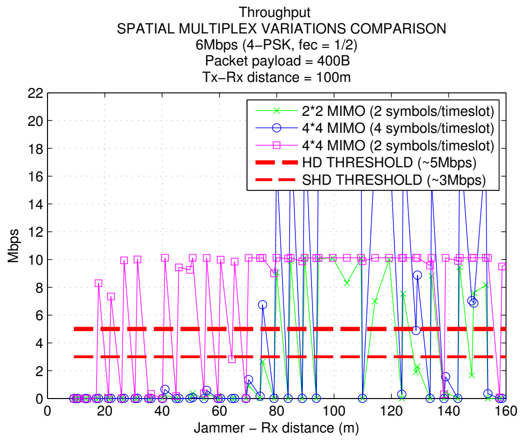
Finally, in Figures 3.7(d), 3.7(e) someone can see the degree of improved performance of higher order MIMO system and Spatial Multiplex variations. Remarkable performance of vSP4 proves the (2.4) section statement that maximizing throughput is not always the optimal strategy. With this algorithm, we managed to double throughput and significantly reduce RF jamming silence range. More complex and advanced algorithms may be developed to perform even better.



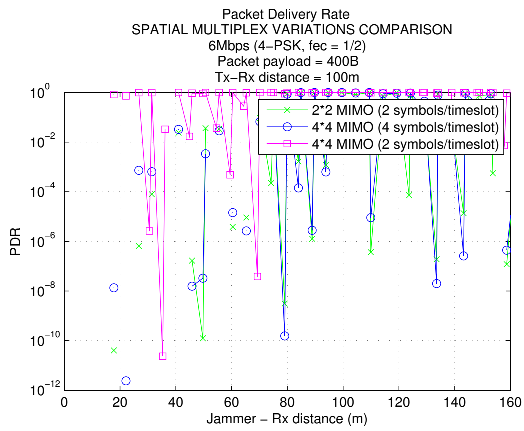
(a) Case 2 of Experiment 2, Throughput to SNR. Comparison of Spatial Multiplex variations and higher order MIMO. Tx-Rx pair distance = 100m



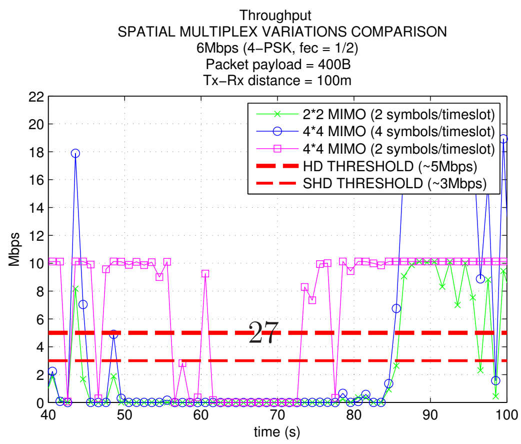
(b) Case 2 of Experiment 2, PDR to SNR. Comparison of Spatial Multiplex variations and higher order MIMO. Tx-Rx pair distance = 100m



(c) Case 2 of Experiment 2, Throughput to Rx-Jn pair distance. Comparison of Spatial Multiplex variations and higher order MIMO. Tx-Rx pair distance = 100m



(d) Case 2 of Experiment 2, PDR to Rx-Jn pair distance. Comparison of Spatial Multiplex variations and higher order MIMO. Tx-Rx pair distance = 100m



(e) Case 2 of Experiment 2, Throughput to Time. Comparison of Spatial Multiplex variations and higher order MIMO. Tx-Rx pair distance = 100m

Figure 3.7: Case 2 of Experiment 2

Chapter 4

Conclusions

By examining all the three cases of experiment 1, its obvious that MIMO systems manage to perform much better than usual SISO system, just by adding one extra antenna, especially when configured properly. Moreover, it is proved that we can eliminate the blockage area to less than 20m up for the long of inter-vehicle distance 100m with an modified MIMO scheme with increased both diversity and throughput.

Capability of supporting video streaming applications, in such an unfriendly environments of 100m communication pair distance and under RF jamming threat, is the real novelty of this work.

Also, hardware of MIMO systems is not restricted to the technique will be used. That is enough to motivate newer and advanced family of Rate Adaptation algorithms. Without considering the payload length tradeoff, usual Rate Adaptation algorithms are limited to change modulation schemes and coding rates. So, robust communication is inversely proportional to throughput while both of them suffer from SISO system tight limits compared to MIMO systems. As proved by these experiments and especially the last case of experiment 2, MIMO systems unlock additional capabilities, so reliability and throughput are not necessary competitive. As higher order MIMO systems are used, such as 4x4 MIMO used in experiment 2, they keep improving performance compared to lower order MIMO systems.

That changes the question we had until now. We dont only have to think how to configure MIMO antennas any more but also how many antennas to use. More is better, under the proper configuration. But, if we safely suppose that 4x4 MIMO, or even higher order, is not prohibitive to be installed, we now also have to consider how many of these antennas should be used to transmit and/or receive, for the following two reasons. Firstly, not all antennas should be always used due to power saving, which is not a primary issue in case of vehicles. The second and most important reason is to be cooperative to network users by not interfering others which is caused by being greedy.

As mentioned earlier, target is not to keep increasing throughput or reliability, but to satisfy each communication case requirements. More than these are useless and harm average network performance.

If we combine all results and conclusions we managed to prove, that MIMO in VANETs, where communication channels are affected by fast environment changes, can significantly improve performance. Also in this network type, communication is exposed to many threats. That is the case that MIMO makes the real difference. It manages to suppress these threats and minimize consequences.

Chapter 5

References

[1] El-Keyi, A.; ElBatt, T.; Fan Bai; Saraydar, C., "MIMO VANETs: Research challenges and opportunities," Computing, Networking and Communications (ICNC), 2012 International Conference on , vol., no., pp.670,676, Jan. 30 2012-Feb. 2 2012 doi: 10.1109/ICCNC.2012.6167507

[2] Theodorakopoulos, A.; Papaioannou, P.; Abbas, T.; Tufvesson, F., "A geometry based stochastic model for MIMO V2V channel simulation in cross-junction scenario," ITS Telecommunications (ITST), 2013 13th International Conference on , vol., no., pp.290,295, 5-7 Nov. 2013 doi: 10.1109/ITST.2013.6685561

[3] Al-Khalil, A. B., Al-Sherbaz, A. and Turner, S. J. (2013) Enhancing the physical layer in V2V communication using OFDM - MIMO techniques. In: Arsuelma'atti, O. (ed.) Proceedings of the 14th Annual Postgraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting. Liverpool: PGNet. 9781902560274.

[4] Viriyasitavat, Wantanee; Boban, Mate; Tsai, Hsin-Mu; Vasilakos, Athanasios, Vehicular Communications: Survey and Challenges of Channel and Propagation Models In: IEEE Vehicular Technology Magazine, vol. 10, no. 2, pp. 55 - 66, June 2015; doi:10.1109/MVT.2015.2410341

[5] Punal, O.; Pereira, C.; Aguiar, A.; Gross, J., "Experimental Characterization and Modeling of RF Jamming Attacks on VANETs," Vehicular Technology, IEEE Transactions on , vol.64, no.2, pp.524,540, Feb. 2015 doi: 10.1109/TVT.2014.2325831

[6] Pereira, Carlos; Aguiar, Ana, "A realistic RF jamming model for vehicular networks: Design and validation," Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on , vol., no., pp.1868,1872, 8-11 Sept. 2013 doi: 10.1109/PIMRC.2013.6666447

[7] Adil Mudasir Malla and Ravi Kant Sahu. Article: Security Attacks with an Effective Solution for DOS Attacks in VANET. International Journal of Computer Applications 66(22):45-49, March 2013.

[8] Belyaev, E.; Vinel, A.; Jonsson, M.; Sjoberg, K., "Live video streaming in IEEE 802.11p vehicular networks: Demonstration of an automotive surveillance application," Computer Communications Workshops (INFOCOM WKSHPS), 2014 IEEE Conference on , vol., no., pp.131,132, April 27 2014-May 2 2014 doi: 10.1109/INFCOMW.2014.6849190